Suppression of the superconducting energy gap in intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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Abstract. We have observed back-bending structures at high bias current in the current-voltage curves of intrinsic Josephson junctions. These structures may be caused by nonequilibrium quasiparticle injection and/or Joule heating. The energy gap suppression varies considerably with temperature. Different levels of the suppression are observed when the same level of current passes through top electrodes of different sizes. Another effect which is seen and discussed, is a super-current "reentrance" of a single intrinsic Josephson junction with high bias current.

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1. Introduction

It is difficult to fabricate Josephson tunnel junctions in high temperature superconductors (HTS), due to the small coherence length of HTS (1-2 nm in the *ab* plane and about 0.2 nm along the *c*-axis). However, the natural layered structure in HTS along the *c*-axis forms tunnelling coupling between adjacent superconducting Cu-O layers with some non-superconducting layers in between acting as the potential barrier (for example, in $Bi_2Sr_2CaCu_2O_{8+\delta}$(BSCCO), there are Bi-O and Sr-O layers) [1, 2]. Each tunnelling junction is about 1.5 nm thick, implying that a thin BSCCO single crystal with a thickness of 150 nm contains 100 intrinsic Josephson junctions (IJJs) in series. The brush-like quasiparticle branch structure in the current-voltage ($I - V$) characteristics is a typical sign of IJJs. However, a suppression of the superconducting energy gap is often observed at a high bias current density. With all the junctions biased into their resistive states, the last quasiparticle branch has two possible appearances. One is an ordinary quasiparticle curve with positive dynamic resistance [3, 4, 5]; the other is a back-bending structure with negative dynamic resistance [6, 7, 8, 9]. This makes it difficult to obtain the real energy gap from $I - V$ curves of IJJs.

We will present our observation of the energy gap suppression in IJJs under high bias current density. We discuss possible mechanism of the energy gap suppression and the temperature dependence. Two different top electrode sizes allow injection of different current densities at the same bias current. We observed clearly different energy gap suppression in IJJs. A novel super-current reentrance phenomena was also observed and will be discussed.

2. Sample fabrication

BSCCO single crystals with critical temperature $T_c \approx 90$ K were grown using the travelling solvent floating zone (TSFZ) method. We fixed a piece of single crystal BSCCO on a Si substrate with polyimide, and then cleaved it to reveal a fresh surface. A thin-film silver layer was evaporated onto this surface. A square mesa with an area of 8×8 μm^2 or 16×16 μm^2 was formed using conventional photolithography and argon-ion etching. The number of junctions in the mesa was controlled by the etching rate and time. A layer of CaF_2 was evaporated to isolate the mesa from the base single crystal right after the etching step. Ultrasonic rinsing in acetone was used to remove the photoresist and the CaF_2 layer on it. The mesa with the silver thin film was subsequently covered with a second silver layer by evaporation. Two separate top electrodes were formed on the mesa by another photolithography and argon ion etching step. Another two base electrodes can be easily formed on the base of the BSCCO chip for four-terminal measurements. The schematic diagram is shown in Figure 1. Note that the junctions in the bottom of the U-shaped mesa are the effective junctions in four-terminal measurements, whereas the junctions formed beneath the electrodes act as a part of the contact resistance (they will be referred to as 'electrode junctions' in what
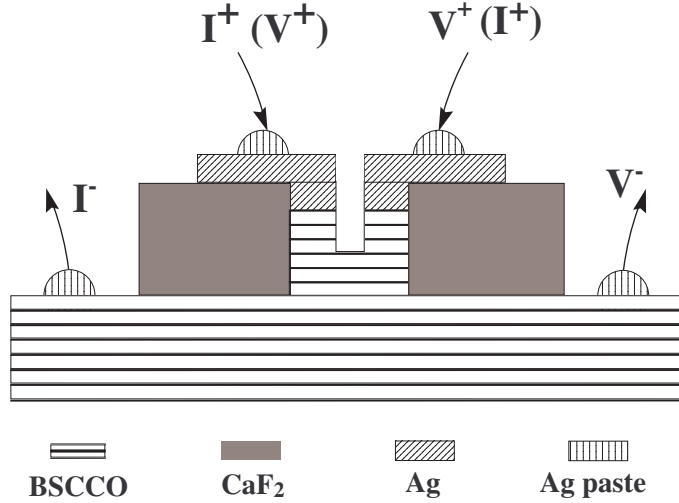
Figure 1. Schematic view of mesa structured IJJs with four-terminal arrangement

follows). A detailed discussion of the IJJs fabrication technology, the properties and the control of the number of junction was published elsewhere [10, 11, 12]. With this fabrication method, we can realize mesa-structured IJJs with any number of junction and eliminate the effect of the surface junction [13].

3. Measurements and discussion

All the measurements were carried out in a cryocooler with a minimal sample temperature of 14 K. Figure 2 shows $I - V$ curves of a sample containing four effective junctions. The size of the mesa in the ab plane is 16×16 μm^2. Two top electrodes with the same size of 6×16 μm^2 are separated by a trench of 4×16 μm^2 formed by the second ion etching. The fabrication parameters are chosen in such a way that we have in the sample 4 effective junctions and 3 electrode junctions. The $I - V$ curves in the inset of Figure 2 show clearly four branches with similar critical currents of $I_c \sim 0.8$ mA. At higher bias current, shown in Figure 2, we observed the well-known back-bending structure of $I - V$ curve with $V_{gmax} = 27$ mV and $V_{gmin} = 6.8$ mV, where V_{gmax} and V_{gmin} denote the average maximal and minimal voltages in the back-bending structure per each junction separately.

Tunnelling spectroscopy experiments and three-probe measurements of the $I - V$ characteristics of ultra small mesa-structured IJJs usually gives a typical value of the superconducting energy gap $\Delta \sim 25 meV$ [5, 14, 15, 16, 17]. The obtained V_{gmax} is obviously less than $2\Delta/e$ (54% of $2\Delta/e$) and V_{gmin} is only 14% of $2\Delta/e$, which illustrate a great suppression of the energy gap under high current density injection.

For comparison, three-terminal measurements were also carried out for the sample sharing a same top electrode for both current bias and voltage measurement. Shown in Figure 3 are the three-terminal $I - V$ curves of the sample with 7 quasiparticle branches,
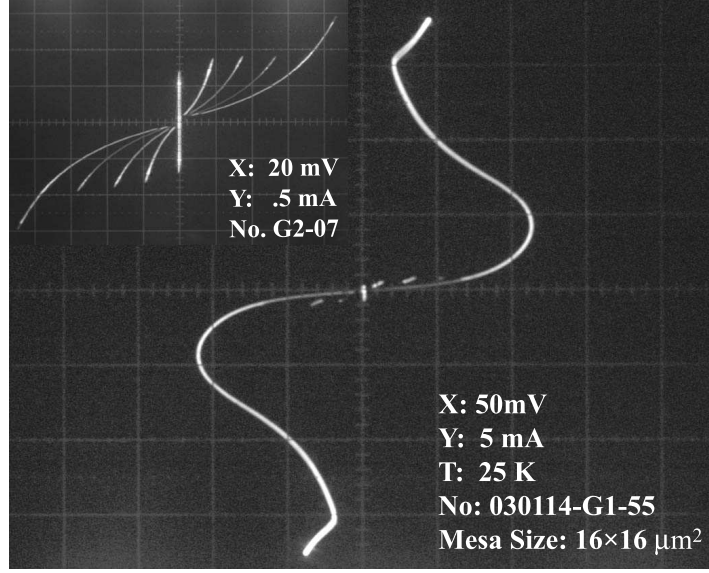
Figure 2. Typical $I - V$ curves of mesa-structured IJJs containing four junctions. The inset shows similar critical currents of the four junctions.

which represents the number of junctions in the mesa. Due to the difference of the critical current, the branches are divided into two groups, one group with $I_c = 0.3$ mA corresponds to the electrode junctions in four-terminal measurements; the other group with $I_c = 0.8$ mA corresponds to the four effective junctions measured in four-terminal method. The magnified figure near the origin shows a junction with a quite small critical current of $I_c = 0.02$ mA (see the inset of Figure 3), which is the surface junction with suppressed superconductivity formed in the interface between the silver layer and the BSCCO mesa [13]. With higher bias current, we also observe a quasiparticle branch with a slight back-bending structure. Because of the inconsistence of those junctions in series in three-terminal measurements, it is difficult for us to evaluate the energy gap quantitatively of each junction. Further analysis and discussions of the suppression of the energy gap will be concentrated on the results of the four-terminal measurements.

To probe the relation between the energy gap suppression and temperature, the dependence of V_{gmax} and V_{gmin} on temperature was measured and is shown in Figure 4. V_{gmax} decreases quickly with increasing temperature; whereas, V_{gmin} remains relatively temperature independence with a slight decrease when the temperature is near T_c. When T=80K, $V_{gmax} = V_{gmin}$, and an abrupt quasiparticle curve was observed instead of a back-bending structure (shown in the inset of Figure 4). Generally, the energy gap voltage $2\Delta/e$ decreases with increasing temperature, so V_{gmax} decreases with a similar trend. On the other hand, the measurement results show that the bias current for V_{gmin} decreases due to the increase of temperature. As a result, the Joule heating effect and the nonequilibrium effect are reduced, making the back-bending structure shrinking. Finally when the temperature is high enough we have $V_{gmax} = V_{gmin}$, and the $I - V$ curve turns into an abrupt quasiparticle curve.
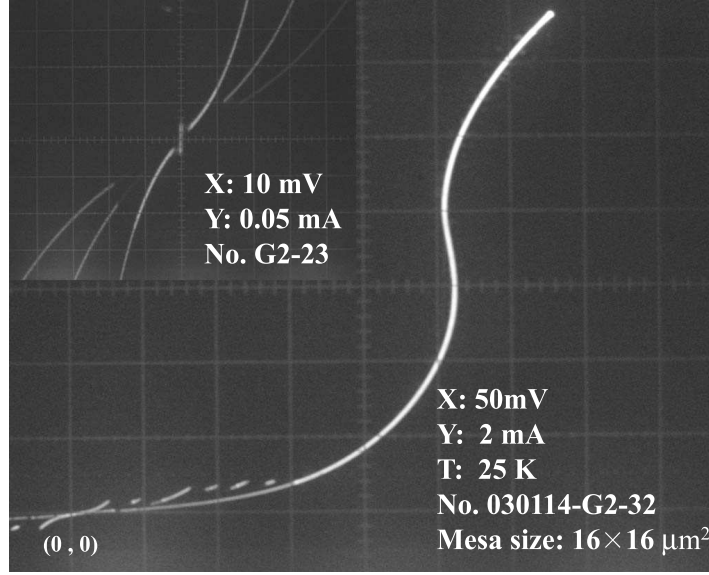
Figure 3. Three-terminal $I - V$ curves of the sample sharing a top electrode for both current bias and voltage measurement. The inset shows the existence of a surface junction with a small critical current
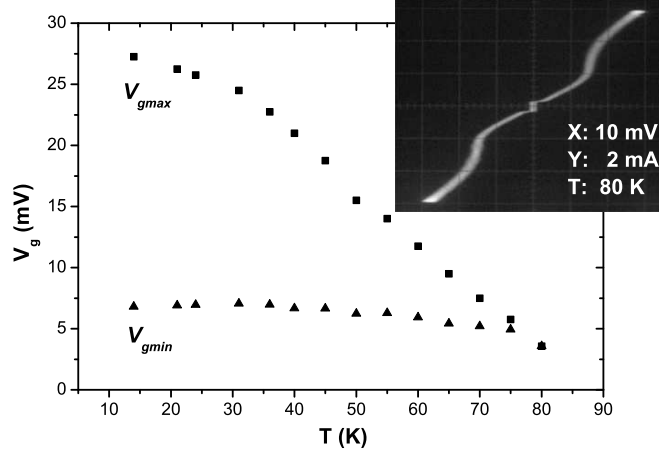

Figure 4. Temperature dependence of V_{gmax} and V_{gmin} for a 4-junction IJJs. The inset shows the $I - V$ curve of the sample at T=80 K

Although quite a few paper have discussed the suppression of the energy gap and attributed to a quasiparticle injection nonequilibrium effect and a Joule-heating effect, not many detailed analysis are available [6, 7, 8, 9]. To further address this problem, we will first look at the possible quasiparticle injection in IJJs. Concerning the c-axis quasiparticle transport, we remark that the effect of the current injection depends strongly on the transmission and energy relaxation of quasiparticles along the c-axis, and they are therefore sensitive to the inter-planar inelastic scattering mechanism in

addition to the in-plane quasiparticle recombination. Since the c-axis dimension of the mesa is much smaller than the lateral dimensions, the effect of quasiparticle injection should be primarily determined by the magnitude of the c-axis quasiparticle relaxation length δ_n^c, even though the in-plane recombination time of excess quasiparticles can be relatively long due to the existence of nodes in the pairing potential [18].

δ_n^c may be expressed as $\delta_n^c = \sqrt{D_n^c \tau_Q}$, where $D_n^c = v_F l_{tr}^c / 3$ is the charge diffusion coefficient along c-axis ($v_F = 2 \times 10^5$ m/s and $l_{tr}^c \sim 1$ nm are the Fermi velocity and transport mean-free path along the c-axis respectively) [19]. It is known that the characteristic quasiparticle relaxation time τ_Q follows the relation [20]

$$\tau_Q(T) \approx \frac{4\tau_E k_B T_c}{\pi \Delta(T)}$$

where τ_E is the inelastic electron-phonon scattering time, and $\Delta(T) = \Delta_0(1 - T/T_c)^v$, with Δ_0 being the zero-temperature superconducting gap and v the order parameter critical exponent. For $T/T_c \ll 1$, with typical $\tau_E \sim 10^{-11}s$ for a cuprate and energy gap $\Delta = 25meV$ for BSCCO, we have $\tau_Q \sim 4ps$, and then deduce $\delta_n^c \sim 16nm$, which is much larger than the thickness of the Cu-O layers. The estimate shows that the quasiparticles can easily pass through the thin Cu-O layers of 3 Å thick, then be injected into the junctions along the c-axis and influence their properties. Recent experiments estimated τ_Q to be about of 100 ps [21]. This would cause an even bigger c-axis quasiparticle relaxation length and stronger quasiparticle injection effect. The quasi-particle injection effect may cause nonequilibrium gap suppression. This has been discussed both theoretically and experimentally for tunnelling junctions made of low temperature superconductors [22, 23, 24, 25, 26, 27]. A similar back-bending structure was also observed in some of their experiments [25, 26].

On the other hand, all the high temperature superconductors have a comparatively low thermal conductivity, which makes them prone to local overheating. Both estimates and experimental results have shown that the temperature of a mesa may increase by several tens of degrees when the bias current is high [28, 29, 30]. Concerning the sample with $I - V$ curves shown in Figure 2&3, the thermal dissipation power for the whole junction stack at the bias current of 4 mA (the bias current for V_{gmax}) can be estimated to be about 1 mW from Figure 3. If we adopt a typical value for the thermal conductance of BSCCO ($40 \sim 70$ K/mW) [30], the possible temperature increase would be over 40 K. Such a serious Joule heating effect will, of course, cause a back-bending structure in the $I - V$ curve. Recently, a short-pulse measurement technique was adopted to minimize the effect of overheating in IJJs, and the back-bending was indeed removed. [31, 32].

Since both Joule heating and nonequilibrium effects originate from a high quasiparticle current density, it is difficult to distinguish the two effects and hard to say which effect is more important than the other for the suppression of the energy gap. Setting aside how to distinguish the two effects, we may concentrate on the relationship between the suppression of the energy gap and high quasiparticle current density injected directly. In the four-terminal measurements, there are two parts of quasiparticle current

which cause the suppression of the energy gap. One is from the electrode junctions through which the bias current passes. A strong quasiparticle current will inject into the effective junctions from the electrode junctions and cause a nonequilibrium effect. Besides, the overheating effect in the top electrode junctions will also cause an increase of the temperature of IJJs. The second part comes from the measured effective junctions themselves. The quasiparticle current in one IJJ will be injected into the adjacent junctions through the common Cu-O layers, and cause a nonequilibrium effect as well as Joule heating. Since the sizes of the electrode junctions are smaller than the effective junctions, the current density in the effective junctions is smaller with the same current through. Hence, the quasiparticle current density in the electrode junctions plays a key role in the suppression of the energy gap, i.e. the size of the top electrode through which the current passes will be an important factor for energy gap suppression.

If we design a mesa with two top electrodes of different size, we should observe different levels of the gap suppression for the same IJJs when the current passes through the two different top electrodes. We did observe such a behavior in the following measurement. For a sample of 3 effective junctions, the sizes of the two top electrodes were $4 \times 8\mu m^2$ (E_1) and $2 \times 8\mu m^2$ (E_2) in a mesa with size of $8 \times 8\mu m^2$ in the ab plane. When the bias current is low (less than $5I_c$), the same $I - V$ curves with three quasiparticle branches were observed with bias current through the two different top electrodes. However, when the bias current $I > 5I_c$, although the back-bending structure was observed in both two cases, the suppression of the energy gap was considerably stronger when the bias current passed through E_2 than when it passed through E_1. This is consistent with the current density through the top electrodes. Furthermore, to minimize the influence of the energy gap suppression from the effective junctions themselves, we did the similar experiment on a sample with only one effective IJJ. Two electrodes, of the sizes $1.5 \times 8\mu m^2$ (E_A) and $4.5 \times 8\mu m^2$ (E_B) respectively, are made on the top of the mesa. The measured $I - V$ curves are shown in Figure 5. When a bias current passes through E_A, the $I - V$ curve showed a back-bending structure ($V_{gmin} = 0.16\frac{2\Delta}{e}$). However, when the bias current is through E_B, instead of the back-bending structure, an ordinary quasiparticle branch was observed with a suppressed gap voltage $V_g/2 = 16.5mV < 25mV$. This indicates that the suppression of the energy gap still existed though it seemed not serious in the $I - V$ curve.

Most surprisingly, in some samples with a single IJJ, a novel super-current reentrance was observed instead of the back-bending structure (shown in Figure 6(a)). This novel phenomena was observed in samples of different sizes ($8 \times 8\mu m^2$ and $16 \times 16\mu m^2$) and under different measurement conditions (samples placed in the vacuum chamber of a cryocooler or directly immersed in Liquid Helium). However, normal multi-branch $I - V$ curves similar to Figure 3 was observed when the sample was measured in three-terminal method.

Such a phenomena can probably be attributed to strong heating effect. As a matter of fact, with increase of the bias current, the nonequilibrium effect and Joule heating effect become stronger and stronger, suppressing the energy gap more and more. When
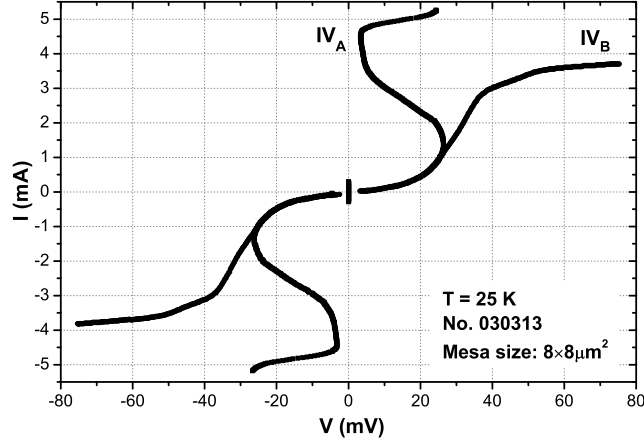
Figure 5. $I-V$ curves of a single IJJ when the bias current passes through different top electrodes. The sizes of the two top electrodes are $1.5 \times 8\mu m^2$ (E_A) and $4.5 \times 8\mu m^2$ (E_B) respectively. IV_i denotes that the bias current passes through top electrode $E_i(i = A, B)$.

the bias current reaches I_{c2}, at which the reentrance occurs, further increase of the temperature may cause some Cu-O layers of the junction to enter the normal state. Regarding the junction we measured, the part of the upper Cu-O layers of the IJJ under the top electrode through which the bias current passes will first enter the normal state due to the poor thermal conductivity. Then the junction is no longer a uniform one. The equivalent circuits are shown in Figure 6(b). In this case, the voltage we measure is the one across that part of junction (J_2) which still remains in the zero-voltage state; i.e., the voltage is zero. When the bias current is high enough, the current through J_2 is larger than its critical current, J_2 will switch to non-zero voltage state and the super-current disappears again. For samples with a few effective junctions, the likeliest part to reach a high temperature is the upmost Cu-O layers beneath the top electrode due to the strong heating effect from the top electrode. Other inner Cu-O layers will have a relatively lower temperature. That may explain why we can only observe the super-current reentrance effect in a single IJJ.

Since a quasiparticle current can always pass through the electrodes and then inject into mesa-structured IJJs, the suppression of the energy gap is difficult to avoid though sometimes it is not serious. Especially, when the sample is fabricated with one top electrode and measured in a 3-terminal method, we often observed a normal quasiparticle branch with a higher energy gap similar at almost 25 meV. Nevertheless, a surface junction is inevitably introduced, which causes series resistance to occur in the measurement.

The double-sided fabrication technology developed by Wang *et al* provides a feasible way to fabricate IJJs with pure superconducting contact electrodes and without the
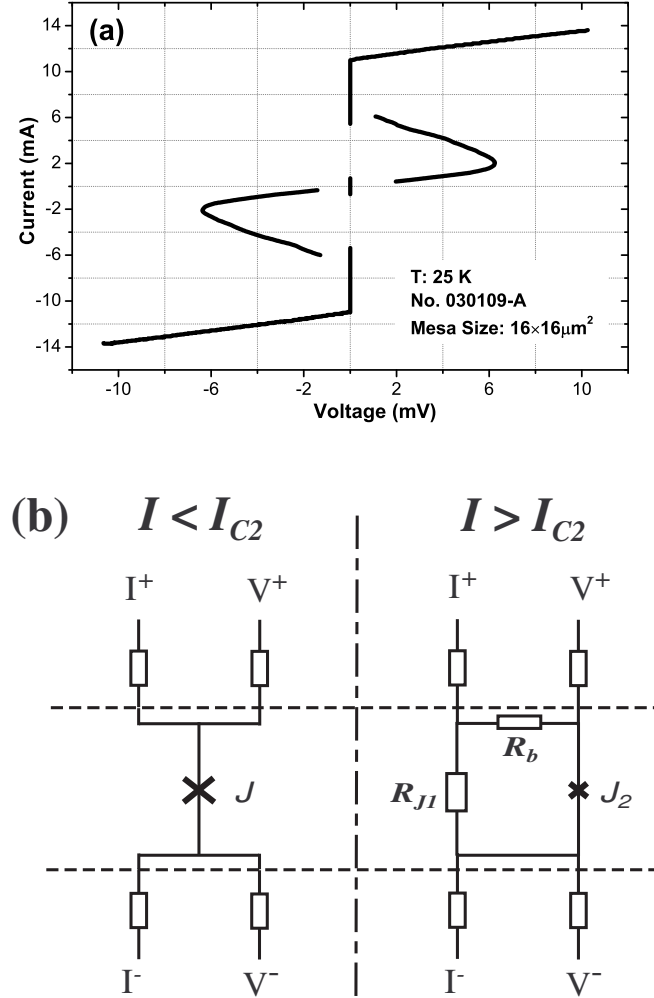
Figure 6. (a) Novel $I-V$ curve of a single IJJ. The sizes of two top electrodes are both $6 \times 16 \mu m^2$; (b) Equivalent circuits for the single IJJ at high bias current, where I_{c2} denotes the bias current at which the reentrance of super-current happens.

influence of quasiparticle current injected through the electrodes [33, 34]. Yet, a back-bending structure was still observed due to a large junction number [33]. The unsolved problem is how to decrease the junction number to 1 with double-sided technology. With this solution, it may be possible to realize an ideal $I-V$ curve of IJJ without energy gap suppression with such a new configuration.

4. Summary

In summary, we observed a suppression of the energy gap under high bias current in mesa-structured IJJs. We have discussed its causes and measured the variance of gap suppression with temperature. With the design of different sizes of top

electrodes in mesa-structured IJJs, we observed different levels of energy gap suppression corresponding to different quasiparticle current densities through the top electrodes. A novel super-current reentrance phenomena was observed and discussed. We suppose that an ideal $I - V$ curve of IJJ with correct energy gap may be observed in single IJJ fabricated by the double-sided technology.

Acknowledgments

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